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US R&D Effort on ITER Magnet Tasks

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The paper presents status of these development tasks, including winding development, inlets and outlets development, internal and bus joints development and testing, insulation development and qualification, vacuum-pressure impregnation, breakout regions, bus supports, TF conductor fabrication development, intermodule structure and materials characterization.

Keywords: Superconducting magnets, Cable-In-Conduit Conductors, Winding, Fabrication, Vacuum Pressure Impregnation

1. Introduction

The US IPO is responsible for supplying the Central Solenoid (CS) with preload and support structure and nine lengths of the Toroidal Field (TF) conductor for ITER machine, currently under construction in Cadarache, France. Several design features that are used in the CS design needed to be developed and qualified during the development and testing activity prior to the completion of the design and entering fabrication stage. This is necessary because the CS is a unique and challenging solenoid, a significant step forward from the past achievements. Industry does not have experience in many aspects of the CS design.

The tolerances on the CS turn location are very tight, especially in the joggles region and therefore the winding machine and auxiliary tools need to be developed in order to assure feasibility of the design. The helium inlets are located in the area of the highest stress and magnetic field, in the area of the lowest temperature margin; therefore they represent a significant fabrication and performance risk. The insulation for CS needs to withstand up to 30 kV and remain structurally robust, a very challenging task, never addressed in fusion magnets in the past.

The ITER CS consists of 6 Modules stacked together with the CS structure that keeps it together under preload in the center of the ITER machine.

The total weight of the CS assembly is about 1000 t; the height is about 16 m and it is 4.3 m in diameter. A detailed description of the CS design is given in [1]. This paper discusses the most critical R&D tasks that are being managed by the US IPO.

2. R&D Tasks

2.1 Joint Development

Joints for the CS conductor are among the most critical elements. There are two types of joints in the CS – interpancake joints and bus joints to be developed. The interpancake joints have two options at the moment – sintered joints and butt joints. Butt joints are more compact and are done after the heat treatment, while sintered joints are more robust and are easier to make. We recently tested a sintered joint that showed excellent resistance. Status of the joint development is given in [2].

One of the important developments we studied is the close out welds of the joint of the choice. Fig. 1 shows the sintered joint closure, but similar closure will have to be done for any in-line joint.

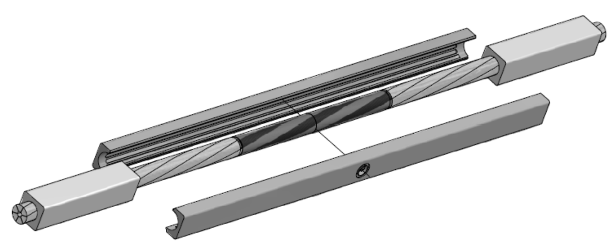

Fig.1 Close out of the sintered joint

The challenge of the task is to produce a full penetration weld in a very close vicinity of the cable without any risk of damage of the cable with a torch or even more stringent requirement – not to overheat the cable above 230 C – melting point of tin. We built a mock up sample with real weld preparations and equipped it with thermocouples and came to conclusion that excursions to 500 C are inevitable for several seconds. But in keeping the lowest possible temperature on the cable surface by frequent stops leads to unacceptable amount of defects at the weld, which

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constitutes by far a higher risk of failure. We introduced additional precautions and lifted temperature control, since the CS strand will hot have free tin in the strands. Several seconds of exposure is not critical for properties of the strand that has a last step of heat treatment at 650 C for 100 hours.

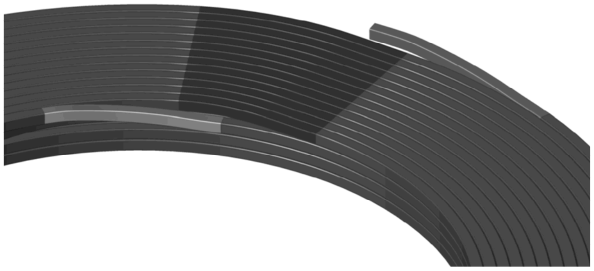

Fig.2. Winding pattern of the CS pancakes. The radial transitions are in a darker grey.

2.3 Winding development

Winding of the CS modules is a very critical operation. The winding pack of a CS module consists of six hexapancakes and one quadropancake in the middle of the winding pack. That means that the winding of the turns goes both outside in and inside out. The winding is done with a constant radius with radial joggles between the turns and axial transitions between the pancakes. The tolerances on the winding pack envelope are +/- 3 mm, that means that position of the turns need to be defined much better to eliminate accumulation error and it is a difficult task with significant uncertainties. In order to study a feasibility of the winding pattern and to obtain parameters for the final winder, we will perform winding trials on the winding machine used for the CSMC fabrication. We will use first 6-7 m long conductors nested on a winding table with clamps in order to fix the stack of the conductor segments, first for constant radius turns and then for the radial transitions. The concept of the fixture for the winding trials is shown in Fig. 3.

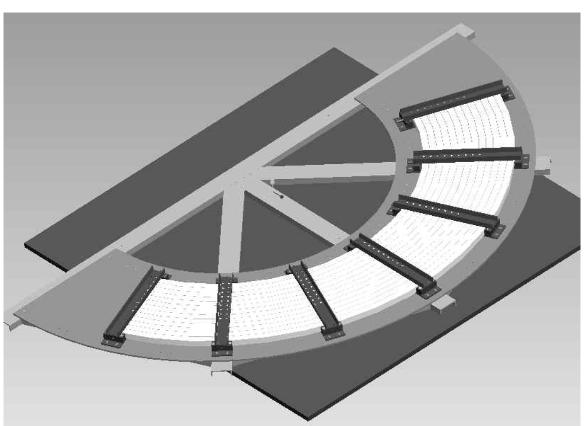

Fig. 3. Concept of winding table fixture

2.4 Development of the Inlets and Outlets

In the inlet and outlet development, three main concerns need to be resolved: practical and low risk fabrication process, acceptable stresses and acceptable hydraulic impedance.

In order to supply the coldest helium into the conductor in the highest field, Helium inlets are located in the bore of the CS modules and outlets are located at the OD. The inlets are in the area where the stresses are the highest in the conduit. Therefore the inlet becomes an area with the highest peak stresses in the module due to inevitable stress concentration in the area of the geometry change.

The inlets developed at the early stage of the CS design were optimized for hoop stresses, but significant compressive stresses generate extremely high peak stresses in the area of inlets. Also, fabrication of the inlets was not optimized for maximum reliability at reasonable cost.

As a result of optimization of this area taking into account all loads and complete scenario we came to an optimized design, which is shown in Fig. 4.

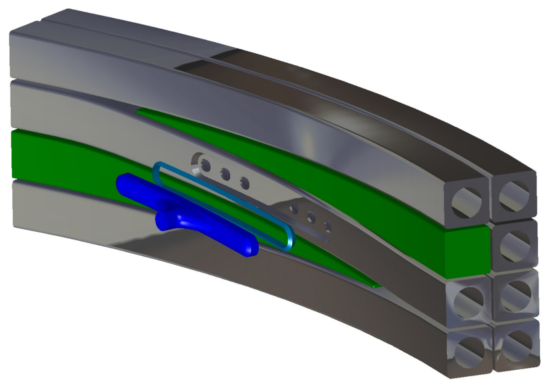

Fig.4. Optimized inlets in the ITER CS, showing also the cover plate and the weld

The design features a thick cover plate to support vertical compressive forces. The penetration holes are elongated in order to reduce stress concentration in round holes. We developed a penetration technique with a puncher, that allows machining the penetration holes first down to 0.25-0.5 mm thick wall in the thinnest area (blind holes) and then punching the hole through with a puncher. After that the punched material is removed by pliers. Such an operation was shown to be safe and the cutting tool never approaches the cable.

As a result of stress optimization we reduced the stresses in the jacket, weld and cover plate, especially in the diffuser by making four holes instead of one, but still, the peak stress level is higher than allowed in the ASME fatigue assessment.

In order to qualify the inlet design, we are planning to qualify the design by cycling testing of the full scale inlet samples in LN2 at double displacement expected in the CS.

In order to assess the hydraulic impedance of the inlet we built a model and analyzed the behavior at supercritical helium flow at the nominal mass flow rate of 8 g/s through the conductor.

The model predicted insignificant pressure drop at the nominal flow – at the level of 1000-1200 Pa, which is equivalent to about 3 m of hydraulic impedance of the regular CICC and that meets the acceptance criterion for the inlet.

2.5 Insulation development

The CS will experience high voltage in operation: up to 12 kV in normal operation and up to 29 kV in the fault conditions. The turn insulation in the CS was designed to meet relatively low turn-to –turn voltage at a reasonable cost. In order to qualify the turn insulation we built two 4x4 arrays and subject them to 1.2 M cycles of compressive load that simulated stresses that the winding pack will experience in the CS operation. Two types of insulation were used in the arrays – bonded and de-bonded, shown in Fig. 6. In the bonded system we used corona treated kapton for good adhesive bonding and kapton is interleaved with the glass tape, which serves as the conduit for the epoxy resin.

Fig. 5. 4x4 test array for CS turn insulation qualification.

In the de-bonded system the kapton is wrapped against the jacket and serves as a slip interface between the conductor and the glass outside the kapton.

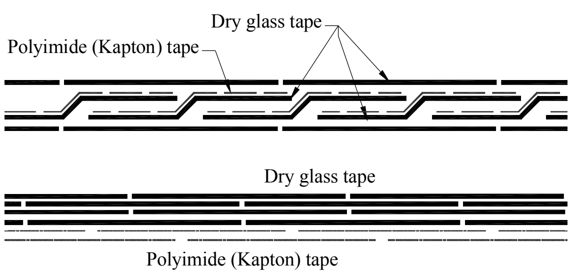

Fig. 6. Bonded (top) and de-bonded (bottom) turn insulations tested

Both systems withstood 1.2 million load cycles to 60 MPa (20 times life) and demonstrated high electrical strength (40+ kV at requirements of 2.2 kV). The bonded system turned out to be more practical in the fabrication aspects. The de-bonded system in reality did not slide that much, which should have been seen in the Young modules of the array. That indicates that the kapton is not effective as a sliding interface. But if it were an effective sliding interface, the stresses in the jacket of the conductors would have been significantly higher and would limit life of the CS. For that reason, the bonded insulation system was selected. The details of this effort are published in [3].

2.5 VPI process development

The VPI process is a critical step in the CS module fabrication. We used the system originally built by B&WXT Company for their SMES project and refurbished and re-commissioned it at Magnet Development Laboratory (MDL) by University of Tennessee in Knoxville.

The system has a mixing tanks, where degassing takes place, plumbing with the controlled temperature, pump with flow rate monitoring and control. The mold is located in a separate autoclave that has a controlled environment, temperature, resin level and vacuum/pressure.

The VPI system was re-commissioned recently at MDL and demonstrated good operation. We impregnated an array of conductors with the epoxy resin, that was used for the CSMC and will be used in a controlled manner and obtained very good permeation of the resin into the array.

2.6 Materials characterization

The US IPO performs a significant amount of the material characterization for magnet tasks. Most of the material characterization work will be done at the National High Magnetic Field Laboratory, Tallahassee, FL. We will do a significant amount of jacket material characterization (over 100 samples) both for bulk material and welds.

We have performed mechanical testing of the butt joints for fatigue and ultimate strength and came to conclusion that the measured butt joint strength 30-40 kN after cycling to a double of nominal strain has a significant safety margin for operation in the CS.

We performed metallographic studies of the welded samples for close out welds around the pancake joints in order to qualify these welds.

We will develop an adequate NDE for the critical component evaluation for production of the CS based on X-ray and UT techniques.

We will perform full characterization of the superconducting strands for the CS conductor in a wide space of parameters, including elevated temperatures and wide strain range.

We plan to test full-scale mock ups of the inlets at LN2 in order to verify sufficient safety margin.

We will test butt welds of the CS conductor in order to verify satisfactory life of the CS in operation.

2.6.1. CS Insert

In order to verify performance of the CS conductor in conditions closest to the operating conditions, we are building an Insert to be tested in the in Japan, at JAEA Central Solenoid Model Coil (CSMC) Test Facility.

The US IPO is responsible for the design and fabrication of the Insert. Preliminary design of the CS Insert is shown in Fig. 7. Since the main interest is the conductor behavior in the DC conditions and after cycling, the structure of the CS Insert could be significantly simplified in comparison with the previously tested CS Insert in the year 2000 [4].

In the CS Insert in the CSMC Test Facility we will be able to simulate strain conditions of the cable in the CS and reach peak field and current in order to obtain a reliable assessment of the CS performance in ITER machine.

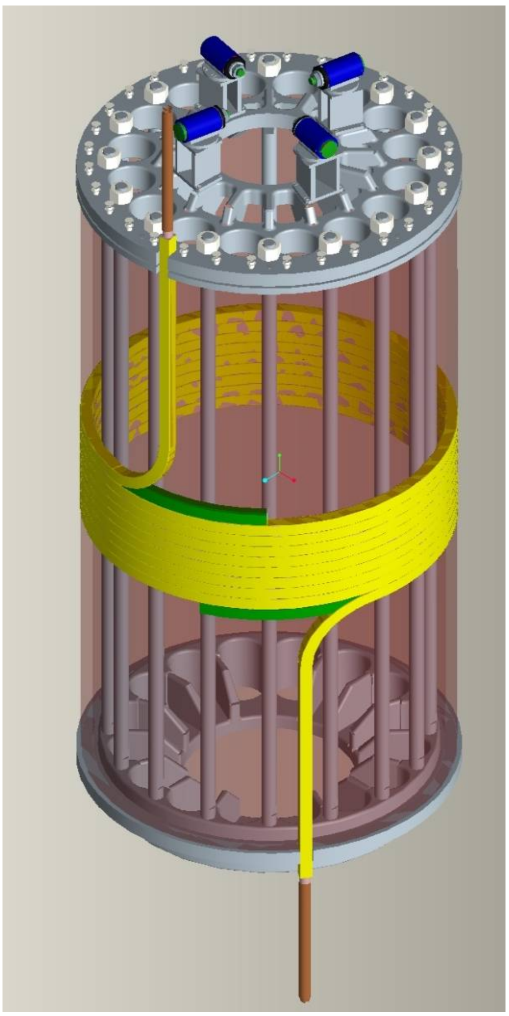

Fig. 7. Preliminary design of the CS Insert

2.7 Terminations support

The original design of the bus supports in 2005 had support structure attached to the tie plates – at some distance from the winding pack. Since 2007, the design has changed and the buses are supported by the structure that is attached (adhesively bonded) to the outer surface of the module. Preliminary structural analysis shows acceptably low stresses, but there is a concern about aging and degradation of the adhesive bond. We will use composite belts that run circumferentially around module or toroidally around winding pack in order to provide additional support to the bus support system. The support needs to address a significant difference in relative motion of the winding pack under cycling load and no longitudinal force on the bus. After completion of the design we plan to build a mock up to establish the feasibility of such an approach and qualify the design.

2.8 Intermodule structure

CS modules are charged with different currents and at some points of the scenario experience lateral forces. In order to keep the modules centered and prevent "walking" that may arise from difference in deformation and mutual sliding of the modules, there should be some constraint in the structure between the modules. At the moment there are two proposals. The first one is centering structural rings in the bore that mechanically center the modules at their interfaces. The other proposal is the radial keys embedded in the intermodule structure. We plan to explore these options and qualify the design in representative mock ups and testing.

Acknowledgments

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